Sustainability Ranking of Solar Power Projects using Multi-Criteria Decision Methods (MCDM)

Kunati Nikhil Reddy[1], Ashish Deep Madisetty[1], and Prasad Pokkunuri[1]
[1] Mahindra École Centrale, Hyderabad (INDIA)

Abstract

Large-scale Solar Power projects are highly capital intensive, however, a great many of them are being commissioned all over the world, in addition to already existing ones. Such renewable energy projects involve a large number of sustainability factors from diverse areas covering technical, environmental, economic and social criteria. Multi-Criteria Decision Methods (MCDM) provide a framework for sustainability evaluation of projects with a range of sustainability factors. To understand these various criteria, existing solar projects in India and China are evaluated based on selected factors using MCDM. Four different methods are adopted, with three different weighing methods, to rank these projects in order of their sustainability and the results analyzed and discussed.

Keywords: Sustainability, Solar Power Projects, Multi-Criteria Decision Methods

1. Introduction

The consequences of climate change, which include disastrous cyclones, floods and droughts to name a few, are being adversely felt across the globe and a trend of increasing frequency of such events has been observed. Conventional coal fired power plants, which have been releasing large amounts of carbon dioxide into the air from the past few decades have majorly contributed to the impact of climate change that we are facing today. The realization and acceptance of climate change by different countries led to the establishment of Kyoto Protocol [6] with the intention of reducing global emission levels through collective efforts of the member countries.

In this era of ushering towards a reality wherein the countries are increasingly trying to become carbon neutral, increasing our reliance on renewable energy and avoiding polluting sources of energy shall come to our rescue. One major form of harnessing renewable energy is developing large scale photovoltaic solar power plants. Two Asian countries - China and India, are the leaders in terms of highest solar photovoltaic capacity added. China and India are aggressively expanding the contribution of solar energy in their energy mix portfolio with year over year growth rates of 33.9% [18] and 34% [19] respectively. Substantial rates of growth can also be observed in Europe and the United States with annual growth rates of 36% [20] and 50% [21] respectively. Around the world, an overall increased emphasis on tapping solar energy can be observed.

However, these solar power plants are difficult to set up owing to the issues arising out of high cost of photovoltaic modules, geographical intricacies, technical complexities among several other factors and hence the development of solar power plants has become capital intensive in nature. A sustainability analysis of the solar project can prove helpful in justifying the proper utilization of this capital since it considers crucial factors of emission reduction and sustainability and ultimately help debt lenders realize the value of their investments in such projects.

This work elaborates the fundamentals of sustainable development and presents multi criteria decision analysis carried out on selected photovoltaic solar energy projects based in India and China. The objective is to bring out a system of ranking for solar projects, never attempted before to the authors' knowledge, that can evaluate the complex solar projects of the world in terms of their sustainability, through multiple approaches. The paper is organized as follows: Sustainable Development is described in the next section, detailing the different types of Indicators used to assess sustainability. Section 3 briefly overviews Multi Criteria Decision Methodology (MCDM) and mentions the different techniques used. These techniques are described in detail next, in Section 4 that also presents project data and the weighing methods used. Results are discussed and analyzed in Section 5 and conclusions are presented in Section 6 while also mentioning possible extensions to this work.

doi:10.18086/swc.2019.28.02 Available at http://proceedings.ises.org

2. Sustainable Development

Sustainable development is defined, following Brundtland Commission's definition [8], as the satisfaction of present needs without compromising the ability of future generations to meet their own needs. Sustainability can be seen as the final goal: which in this case is to optimize land usage, minimize emissions, maximize output for a reasonable amount of investment, resulting in a balance of social and economic activities and the environment. Sustainability assessment is crucial to understand a project's contribution towards sustainable development. The intricacies of sustainable development can be better understood by the indicators which have been laid down below.

2.1 Indicators of Sustainable Development (Wang et al, 2009):

Economic: In terms of economy, costs generally mean the investment, operation and maintenance, or other unavoidable costs of projects. Operational life shows the lifetime of technology or project. The cost effectiveness of a project is always required for sustainability analysis in all energy studies and contributes as a major factor in determining its sustainability.

Social: In order to measure sustainable development contribution of a particular project, social pillar of sustainability must also be considered. Examples of social sub-criteria are job creation and employment which states the impact on the local economy, impact on human health, impact on life quality and society, and public support etc... Depending on project's purposes, more criteria can be chosen to assess social impact of project.

Environmental: The main goal of solar power projects is contributing to emission reductions. Thus, in order to assess the sustainability of any given project, the determination of environmental criteria is an essential step. Emissions/pollutants mainly constitutes CO2 and other potential pollutants depending on type of the solar power plant. Here, we have considered the CO2 emissions saved in tons as a criterion. Land use is also major criterion with respect to life in the region and natural reserves

Technical: The main objective of these indicators is to compare operating performances of the solar power projects. Here, we have considered operating capacity in MW, electricity generated per year in MWh, period of construction in years, capacity factor and levelized cost of electricity.

Risk: it is defined as the intentional interaction with uncertainty, which might probably tend to lose something of value. Due to the high uncertainty and being a probabilistic factor, risk has been omitted from the sustainability evaluation in this particular case.

3. Multi Criteria Decision Methodology (MCDM)

MCDM is a decision support tool (Simsek et al, 2018) that is helpful in choosing the best alternative by combining alternatives' performance across various contradicting, qualitative & quantitative criteria, which address complex problems featuring high uncertainty along with conflicting objectives. The objective of MCDM is not to suggest the best decision, but to aid in decision making to select the best among the shortlisted alternative that fulfils the requirements and is in line with the required preferences. Some of the most prominent and widely used MCDM techniques include Analytical Hierarchy Process (AHP) (Dos Santos et al, 2019), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) among several others.

MCDM has a wide spectrum of applications in fields such as Operation Research, Sustainable Energy and Environment, Manufacturing systems, Supply Chain Management, Construction and Project Management and several other fields. It is majorly used in decision-making in many diverse fields like choosing the best airplane for a commercial airline network to selecting suppliers in a broad spectrum of suppliers in a supply chain.

In solar energy projects, application of MCDM can help reduce the complexity in decision-making process which involves dealing with multiple criterion, each having their own unique weightage. MCDM techniques have been used earlier to rank concentrated solar projects [5] and evaluate their sustainability.

4. Analysis

4.1 Selection of Criteria:

From the indicators of sustainable development, the following criteria have been considered in this project: operating capacity(MW), Electricity(MWh/Yr), Construction Period(Yr), Capacity Factor(%), LCOE, Investment(Crores), O & M (Crores/Yr), Emission Saved (tCO2e), Land (ha), Jobs (No of people).

4.2 Data collection:

Once the criteria were selected, the values of these criteria for the selected projects, as in Table 1, have been gathered from various reliable internet sources [9 – 17] which include the respective state government power generation websites, Mercom among a few others. The operation and maintenance costs has been estimated to be ₹ 6.5 lakhs annually for servicing a 1MW plant, from actual project database. [22]

Table 1: Data Matrix

	Project Name	Kamuthi Solar Park	Pavagada Solar Park	Kurnool Solar Park	Longyangxia Dam Solar Park	Huanghe Hydropower Golmud Solar Park
Technical Indicators	Operating Capacity (MW) (B)	648	1400	1000	850	200
	Electricity (MWh/Yr) (B)	1350000	1600000	1400000	220000	317000
	Construction Period (Yr) (NB)	0.67	2	2	4	2
	Capacity Factor (%) (B)	23.8	13	16.147	8.8	18
	LCOE (NB) (Crores)	0.00016	0.00045	0.00024	0.00144	0.00053
Economic Indicators	Investments (Crores) (NB)	4550	14800	7000	6545	3779
	O & M (Crores/Yr) (NB)	42	130	65	55.25	20
Environmental Indicators	Emission (tCO2e) (B)	1038351	1190747	1041904	1637277	235917
	Land (ha) (NB)	1011	5000	2400	2700	564
Social Indicators	Jobs (Personnel) (NB)	800	8000	2500	2000	400

Note: 1 lakh = 0.1 million, 1 crore = 10 million, 1Rupee (₹) = 0.014 US Dollar (As on 26th July, 2019

4.3 Scaling to 1000 MW:

For the above collected data, the values of the respective criterion are interpolated considering the operating capacity of all the power plants as 1000 MW to conduct the analysis on a uniform basis. In this way the best among the criteria for 1000 MW can be obtained of which all may not be from the same project in the given subset. The best requirements of the criteria among the subset maybe termed as the ideal condition.

Table 2: Modified Data Matrix

	Project Name	Kamuthi Solar Park	Pavagada Solar Park	Kurnool Solar Park	Longyangxia Dam Solar Park	Huanghe Hydropower Golmud Solar Park
Technical Indicators	Operating Capacity (MW)	1000	1000	1000	1000	1000
	Electricity (MWh/Yr)	2083333	1142857	1400000	258823	1585000
	Construction Period (Yr)	1	1.4	2	4.7	10
	Capacity Factor (%)	23.8	13	16.147	8.8	18
	LCOE	0.00016	0.00045	0.00024	0.00144	0.00053
Economic Indicators	Investments (Crores)	7021	10571	7000	7700	18895
	O & M (Crores)	65	93	65	65	100
Environmental Indicators	Emission (tCO2e)	1602393	850533	1041904	1926208	1179585
	Land (ha)	1560	3571	2400	3176	2820
Social Indicators	Jobs (Personnel)	1234	5714	2500	2352	2000

4.4 Normalization:

Since all the criteria are measured in different units, the need for normalization arises so that the evaluation of sustainability index can be calculated. The normalized value will be a non-dimensional quantity. The criteria are further classified as beneficial and non-beneficial.

4.4.1 Beneficial(B): A quantity for which a higher value has positive impact on the project's sustainability

Normalizing formula: $Y_{ij} = X_{ij}/\text{Max}\ (X_{ij})$

4.4.2Non-Beneficial (NB): A quantity for which a lower value positive impact on the project sustainability

Normalizing formula: $Y_{ij} = \text{Min}\ (X_{ij})/X_{ij}$

Refer Table1 for the classification of Beneficial(B) and Non-Beneficial (NB) criteria

4.5 Weighting Factors:

The normalized value of each criterion is multiplied by a certain weight according to the order of importance and the sum of all the weights is equivalent to 1. The weights have been assigned for four different scenarios.

4.5.1 Equal Weights: All the 10 different criterion have a weight of 0.1 each.

4.5.2 Entropy: [1] This is an objective weighting method which is used when the numerical values of criteria are known. It makes it possible to value criteria objectively and to see the relation between criteria evidently. The entropy indicates the extent up to which criteria demonstrate the information of system and reflects the magnitude of uncertainty of the criteria. It is calculated as follows:

$$X_j = \sum_{i=1}^{m} x_{ij}\ ;\ j = 1,2,\dots,n$$

where x_{ij} = evolution matrix element value at position (i,j)

Then the entropy measure of j_{th} criteria constant intensity is calculated as

$$e_j = -\frac{1}{lnm}\sum_{i=1}^{m}\frac{x_{ij}}{X_j}ln\frac{x_{ij}}{X_j}$$

where m = number of alternatives/projects considered

Table 3: Entropy weights

Capacity	0.0644
Electricity	0.1033
Construction Period	0.0666
Capacity Factor	0.1039
LCOE	0.1440
Investment	0.0612
O & M	0.0800
Emission	0.0574
Land	0.1085
Jobs	0.2104

4.5.3 Analytical Hierarchy Process (AHP) (Majumder and Saha, 2016): The application of AHP begins with a problem being decomposed into a hierarchy of criteria so as to be more easily analysed and compared in an independent manner. After this logical hierarchy is constructed, the decision makers can systematically assess the alternatives by making pair-wise comparisons for each of the chosen criteria. This comparison may use concrete data from the alternatives or human judgments as a way to input subjacent information. AHP transforms the comparisons, which are most often empirical, into numerical values that are further processed and compared. The weight of each factor allows the assessment of each one of the elements inside the defined hierarchy. This capability of converting empirical data into mathematical models is the main distinctive contribution of the AHP technique when contrasted with other comparing techniques.

Table 4: AHP Weights

Capacity	0.15
Electricity	0.27
Construction Period	0.01
Capacity Factor	0.04
LCOE	0.09
Investment	0.18
O & M	0.14
Emission	0.04
Land	0.06
Jobs	0.02

4.6 Analysis:

The analysis is done using four different MCDM techniques by applying the weights obtained through AHP, Entropy and Equal Weights cases.

4.6.1 Weighted Sum Model (WSM):

In this method the criteria values are normalized and then the normalized value of each criteria is multiplied by the weights to obtain the criteria score. The maximum of the criteria score can only be as high as the weight of the criteria. The sum of all criteria scores for a single power plant will be the sustainability score of the power plant. The higher the sustainability score the power plant is determined as more sustainable.

4.6.2 Weighted Product Model (WPM):

This method is similar to WSM. In WPM, the step that involves multiplying the weights to the normalized values is replaced with raising the normalized values to the power of the weights.

4.6.3 Weighted Aggregated Sum Product Assessment (WASPAS):

WASPAS is a multi-criteria decision analysis method that is a combination of Weighted Sum Model (WSM) also known as the normalized MCDM in this paper and Weighted Product Model (WPM) in order to rank a set of alternatives. The obtained scores by both the methods are added to give us the score for each project.

4.6.4 Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS):

TOPSIS is a multi-criteria decision making tool that evaluates a parameter using the shortest geometric distance between the said parameter and an evaluated positive ideal solution and the longest geometric distance from the negative ideal solution. The normalization follows the formulae of

$$X_{ij} = \frac{x_{ij}}{\sqrt{\Sigma {x_{ij}}^2}}$$

The weighted normalised matrix is then calculated by multiplying the weights of each criteria to the normalised values. Then the worst alternative and the best alternative is determined for each criteria based on which criteria is beneficial or non-beneficial. For example, the least value for in a non-beneficial criteria is the best alternative and vice-versa. The square of the distance between the given alternative and the worst or best alternative based on whether it is beneficial or non-beneficial is calculated for every parameter and all of that is added up for a given alternative (In our case, it is the solar projects). We then obtain a column of best alternatives and worst alternatives each. The alternatives are organised by calculating their similarity to the worst condition and ranked according to the obtained similarity.

5. Results

The sustainability scores for the five projects have been calculated by using the weights from the three weighting methods in each of the four MCDM techniques as shown in Tab. 5 along with a column having the ideal score for each project. This ideal version of a solar project reflects perfect balance of the criteria with the highest level of sustainability.

Table 5: Sustainability Score Matrix

	Kamuthi	Pavagada	Kurnool	Longyanxia	Huanghe	Ideal
WSM (AHP)	0.992	0.625	0.814	0.594	0.642	1
WPM(AHP)	0.992	0.596	0.794	0.412	0.595	1
WASPAS(AHP)	0.992	0.61	0.804	0.503	0.618	1
TOPSIS(AHP)	0.979	0.557	0.728	0.359	0.524	1
WSM (Eq. WT)	0.983	0.563	0.721	0.575	0.573	1
WPM (Eq. WT)	0.981	0.523	0.696	0.439	0.495	1
WASPAS (Eq. WT)	0.982	0.543	0.708	0.507	0.534	1
TOPSIS (Eq. WT)	0.945	0.543	0.746	0.446	0.459	1
WSM (Entropy)	0.99	0.493	0.681	0.503	0.572	1
WPM (Entropy)	0.991	0.45	0.663	0.386	0.514	1
WASPAS (Entropy)	0.99	0.472	0.672	0.445	0.543	1
TOPSIS (Entropy)	0.975	0.417	0.742	0.44	0.63	1

These five projects are further ranked as shown in Figures 1, 2, 3, & 4 on the basis of the MCDM technique followed and the category of weighting factors considered. In these figures Ideal project is considered to have zero ranking and hence not shown.

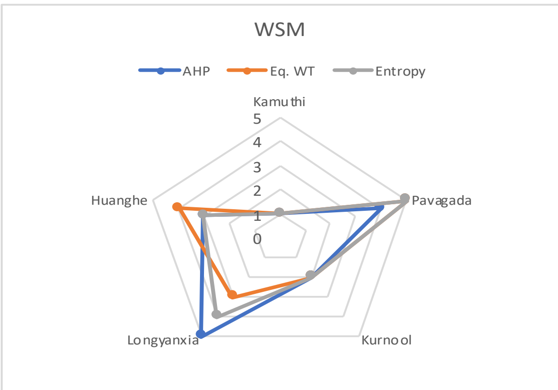


Fig. 1: Weighted Sum Method Ranking

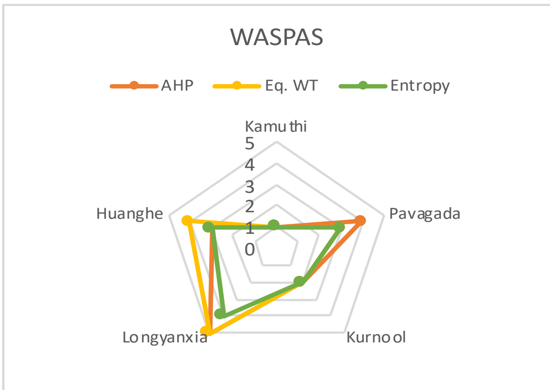


Fig.2 : Weighted Aggregated Sum Product Assessment Ranking

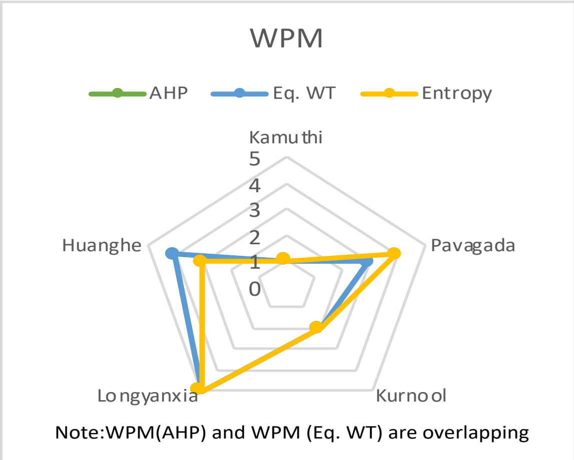


Fig. 3: Weighted Product Method Ranking

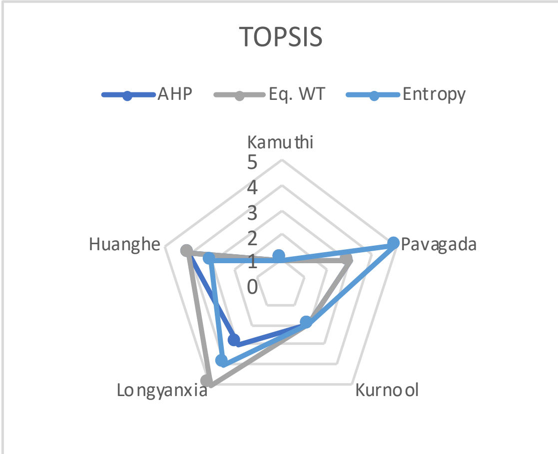


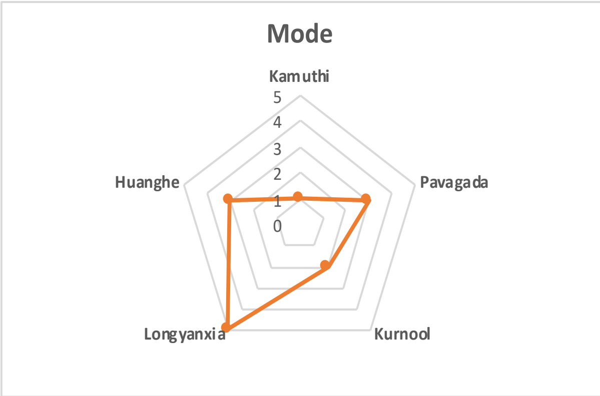
Fig. 4: Technique for Order of Preference by Similarity to Ideal Solution Ranking

As no multi criteria method is perfectly fit for calculating the score, this paper considers a total of 12 rankings coming from four MCDM methodologies and three weighting method and the mode of these set of 12 rankings of a particular projects helps assign the final ranking to the individual project. Table 6 below shows the set of rankings along with the mode and Fig. 6 shows the final ranking obtained through mode.

Table 6: Final Ranking Matrix

	Kamuthi	Pavagada	Kurnool	Longyanxia	Huanghe
WSM (AHP)	1	4	2	5	3
WPM(AHP)	1	3	2	5	4
WASPAS(AHP)	1	4	2	5	3
TOPSIS(AHP)	1	3	2	3	4
WSM (Eq. WT)	1	5	2	3	4
WPM (Eq. WT)	1	3	2	5	4
WASPAS (Eq. WT)	1	3	2	5	4
TOPSIS (Eq. WT)	1	3	2	5	4
WSM (Entropy)	1	5	2	4	3
WPM (Entropy)	1	4	2	5	3
WASPAS (Entropy)	1	3	2	4	3
TOPSIS (Entropy)	1	5	2	4	3
Mode	1	3	2	5	3

Fig. 5: Final Ranking



6. Conclusion

Five different solar power projects – three in India, two in China – are compared for their sustainability. A total of ten criteria – spanning across technical, economic, environmental, and social indicators – are used to obtain sustainability scores. Firstly these criteria are weighted, using Equal Weights, Entropy, and AHP methods. Using these three different sets of weights, the projects are then scored for their sustainability using WSM, WPM, WASPAS, and TOPSIS methods, which apply the principles of MCDM in their unique ways. Each scoring is compared to a hypothetical "Ideal Project" which combines best values of all ten criteria to obtain a sustainability score of 1. The rankings so obtained among the five projects are fairly consistent across each of the twelve scorings. The final ranking is taken as the mode of individual ranks obtained using the twelve scorings. The slight variation in ranks among the different scorings occurs only for the middle- and lower-ranked projects. The top two ranks are consistent across all the twelve scores. This can be attributed to the differences in the individual methods used, and also to the way project criteria are normalized before ranking.

Further, the criteria used do not constitute an exhaustive set. Also, MCDM methods do not consider overlap and conflicting aspects of the objectives implied by the criteria. For this purpose a detailed trade-offs analysis, as described by de Magalhães et al (2019) is necessary, this represents scope for future work. It is expected that using a larger number of criteria will reduce the variability in rankings, but could also exacerbate trade-off conditions, if not chosen properly.

An exhaustive ranking study is suggested, incorporating multiple projects, using more criteria, and also a wider variety of weighing and scoring methods, before a standardized Sustainability Score can be adopted for use by government agencies, banking and financial institutions, see for example Cubas-Diaz et al (2018).

7. References

[1]. Cubas-Diaz M., and Martinez Sedano M. A., 2018. Do Credit Ratings Take into Account the Sustainability Performance of Companies? Sustainability, 10: 4272.

[2]. de Magalhães R. F., Danilevicz Ã. de M. F., and Palazzo J., 2019. Managing trade-offs in complex scenarios: A decision-making tool for sustainability projects. Journal of Cleaner Production, 212: 447 – 460.

[3]. Dos Santos P. H., Neves S. M., Sant'Anna D. O., de Oliveira C. H., and Carvalho H. D., 2019. The analytic hierarchy process supporting decision making for sustainable development: An overview of applications. Journal of Cleaner Production, 212: 119 – 138.

[4]. Majumder M., and Saha A. K., 2016. Feasibility Model of Solar Energy Plants by ANN and MCDM Techniques. Springer Briefs in Energy.

[5]. Simsek Y., Watts D., Escobar R., 2018. Sustainability evaluation of Concentrated Solar Power (CSP) projects under Clean Development Mechanism (CDM) by using Multi Criteria Decision Method (MCDM). Renewable and Sustainable Energy Reviews, 93: 421 – 438.

[6]. United Nations, Kyoto Protocol. Available Online at http://unfcc.int/kyoto_protocol/items/2830.php

[7]. Wang J.-J., Jing Y.-Y., Zhang C.-F., and Zhao J.-H., 2009. Review on multi-criteria decision analysis aid in sustainable energy decision making. Renewable and Sustainable Energy Reviews, 13: 2263 – 2278.

[8]. WCED, 1987. Our Common Future (Brundtland Report). Oxford University Press, Oxford, UK.

[9]. http://apspcl.ap.gov.in/content/kurnoolultramegasolarparks

[10]. http://www.kspdcl.in/sp_docs/Environment%20Assesment%20impact%20report%20Feb-16.pdf

[11]. https://gpcl.gujarat.gov.in/showpage.aspx?contentid=15

[12]. https://mercomindia.com/pavagada-solar-park-projects

[13]. https://urvishdave.wordpress.com/2013/03/21/charanka-solar-park-overview-pv-modules-inverter technology-details-of-gujarat-solar-park-projects/

[14]. https://www.alternative-energies.net/longyangxia-dam-solar-park-in-china-is-now-the-biggest-solar-farm-in-the-world/

[15]. https://www.esmap.org/node/56764

[16]. https://www.karnataka.com/industry/pavagada-solar-park/

[17]. https://www.solarquarter.com/index.php/3148-list-of-solar-parks-in-india

[18]. http://taiyangnews.info/markets/china-installed-44-gw-solar-pv-in-2018-nea/

[19]. https://mercomindia.com/solar-power-increased-34-yoy-q1-2019/

[20]. http://www.solarpowereurope.org/wp-content/uploads/2018/09/Global-Market-Outlook-2018-2022.pdf

[21]. https://www.seia.org/solar-industry-research-data